NASA Technical Memorandum 83205

DYNAMIC MOIRÉ METHODS FOR DETECTION OF LOOSENED SPACE SHUTTLE TILES

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SEPTEMBER 1981

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SUMMARY

Moiré fringe methods for detecting loose space Shuttle tiles have been investigated with a test panel consisting of a loose tile surrounded by four securely bonded tiles. The test panel was excited from 20 to 150 Hz with in-plane sinusoidal acceleration of 2 g (peak). If the Shuttle orbiter can be subjected to periodic excitation of 1 to 2 g (peak) and rigid-body periodic displacements do not mask the change in the Moiré pattern due to tile looseness, then the use of projected Moiré fringes to detect out-of-plane rocking appears to be the most viable indicator of tile looseness since no modifications to the tiles are required.

INTRODUCTION

The orbiter's conventional aircraft-like aluminum skin is protected on ascent and reentry by a mosaic of approximately 30,000 thermally insulating ceramic tiles. The rather brittle tiles are isolated from the strain of the skin itself by special nylon felt strain isolation pads (SIP). The skin-SIP and SIP-tile interfaces are bonded with room-temperature-vulcanizing (RTV) silicone adhesive. The combination known as the thermal protection system (TPS) has been critically reviewed by Cooper and Holloway (ref. 1).

If the TPS is cyclically loaded, as might be expected during a mission due to acoustics, structural vibration, and transonic shock, sufficient loosening of SIP or SIP bonds might warrant replacement. It is therefore desirable to have a quick and nondestructive method to indicate which SIP are suspect without lengthening the turnaround time between orbiter missions.

Ideally one would like to survey large areas at a time (global) remotely and passively in the course of routine maintenance. Further, the technique should require no tile modification and be relatively simple to interpret. Photogrammetric methods (which can determine the static tile displacements) would seem to offer most of these advantages except that displacement appears to be an insufficient flag for a loosened tile since "a tile once subjected to a low number of stress reversals could be positioned anywhere within a 0.25-cm (0.10 inch) range" (ref. 2). Hence the static displacement depends on the most recent loading experienced by the tile and is not by itself a sufficient indicator of tile looseness.

If controlled loading can be imposed on the tiles, then dynamic methods may adequately flag loosened tiles. Small periodic excitation can be used to exploit resonant behavior (ref. 3). The measurement range of the selected dynamic method should improve on the unaided eye limit (approximately 0.25 mm) without being unduly sensitive to the surface structure irregularities of the tiles. The purpose of this paper is to consider dynamic Moiré methods for

detection of loosened tiles since Moiré methods are relatively simple to implement and can be used to magnify displacements by several orders of magnitude.

SYMBOLS

f	geometric repeat distance of Moiré grid patterns
g	acceleration of gravity
$D,\overline{D}$	distance between analyzer and projected grid
ℓ,m,n	ordinal indices for grid lines
L	reference dimension
p	period (pitch) of a ruling
α	incident angle of projected light
β	viewing angle of projected fringes
δ	fringe spacing
Δ	small change in associated quantity
θ	angle between rulings of specimen and master grating

BASIC CONCEPTS

Moiré is the French name for a fabric known as watered-silk which exhibits patterns of light and dark bands. The effect manifests itself whenever two or more similar patterns are superimposed. Although a nuisance in some applications such as multicolor printing which entails the use of screened images, the phenomenon can be used to advantage for measuring small displacements. The quantitative nature of Moiré is easily demonstrated using linear rulings. If the transparent and opaque segments have equal width, then the pattern is completely characterized by its period p (often called the pitch). For convenience, one of the rulings (held fixed) is referred to as the master while the ruling which is associated with or attached to the object to be measured is referred to as the specimen ruling. The directions perpendicular to and along the rulings are called, respectively, principal and secondary.

In figure 1 two linear arrays are superimposed at an angle θ and a third (also linear) pattern of Moiré fringes is generated. The normal to the Moiré fringes so formed is along the bisector of the angle between the rulings.

Referring to the bottom of the figure if δ represents the spacing of the fringes and f the repeat distance of the elementary rhomboids, then

$$f \cos(\theta/2) = \delta \tag{1a}$$

and

$$f \sin(\theta) = p \tag{1b}$$

Using the half-angle formula and eliminating the variable f

$$\delta = \frac{p}{2 \sin (\theta/2)} \tag{2}$$

The pitch is scaled up by a factor $[2 \sin(\theta/2)]^{-1}$ or conversely a measurement of δ using known grids provides an accurate method for determining small angles. Furthermore if either ruling is moved along its principal direction by an amount p, the Moiré fringe pattern also translates by its fundamental period δ. Thus displacements not detected by the unaided eye are made readily visible by Moiré techniques. Translation of the Moiré pattern varies directly as the cosine of the angle between the direction of motion of a ruling and its principal direction so that motion of a ruling in its secondary direction produces no motion of the Moiré pattern. If the rulings are mismatched having period p and p' then the relationship is only slightly more complicated (ref. 4).

$$\delta = \frac{p\, p'}{\left[p^2 \sin^2 + (p\cos\theta - p')^2\right]^{1/2}} \tag{3}$$

For identical grids which are not in contact, the more remote grid will have an apparent finer pitch.

If projected fringes are used, sensitivity to in-plane displacements of the object is lost. Perspective also becomes very important since the Moiré pattern varies with view direction. Consider a master grating illuminated by collimated light incident at angle α as in figure 2. Shadows of the grating are projected onto a diffuse surface which for simplicity is assumed to be plane and parallel to the grating plane. Obviously when viewed from the direction of the light source no Moiré fringes are seen because only one pattern is perceived. (The grating shadow is directly behind the master.) As the view angle becomes normal while viewing a shadow, n grid lines are traversed and beat against the original.

From the geometry, if n rulings separate entrance and exit rays, then

$$\tan \alpha = \frac{np}{D}$$

Proceeding further through an additional angle β , m more lines are encountered so that

$$\tan \beta = \frac{mp}{D}$$

Combining the two results

$$\tan \alpha + \tan \beta = \frac{\ell p}{D} \tag{4}$$

where $\ell = m + n$. With fixed viewing angles, $\Delta\ell \propto \Delta D$ (i.e., fringe number varies directly as D).

An interesting case germane to this study is "out-of-plane rocking." This occurs as in figure 3 when a panel (tile) is fixed at a point or along a line at a distance $\bar{D}$ and allowed to rotate through some angle $\Delta\theta$. Then the fringes appear to be fixed near the stationary point and extend or compress to either side as the object rotates. This phenomenon can be masked by rigid-body periodic displacements which simultaneously alter $\bar{D}$ causing the entire pattern to sweep back and forth while the compression-extension takes place due to rocking. From the figure

$$(D_2 - D_1)/L = \sin \Delta\theta \simeq \Delta\theta \tag{5}$$

the last equality being consistent with the expected small angles of rocking. With the viewing geometry fixed equation (4) can be rewritten in terms of ΔD and substituted in equation (5) to give

$$\Delta\theta \simeq \Delta\ell \frac{p}{(\tan \alpha + \tan \beta)L} \tag{6}$$

For $\alpha = \beta = 45^{o}$, L = 15 cm and a modest p = 0.25 mm, the sensitivity to out-of-plane rocking is 0.05 degrees/fringe.

EXPERIMENTAL INVESTIGATIONS AND RESULTS

The tiles on the upper surface of the orbiter have a white ceramic coating with a low solar absorptance to help maintain low temperature in orbit. The tiles on the lower surface, which will encounter the greater reentry heating loads, have a black ceramic coating with high surface emittance to make them efficient radiators. Surprisingly, even the black tiles are amenable to photo-optical methods as demonstrated by the visibility of the widely space projected grid lines on the black tile surface in figure 4a. That there is some specular advantage can be seen in figure 4b where a laser beam incident on the tile "reflects" a slightly diffused cone of light which is shown irradiating a card. This enhancement in the specular

direction might prove helpful in choosing viewing geometry. In figure 4c a collimated laser beam is used to project a 12-line/mm ruling onto the surface of the tile. The Moiré fringes are starting to break up due to the surface topology thus establishing a practical lower limit for p in the above formulas of 0.08 mm.

The major use of Moiré has been to measure strain in applied mechanics. While not pre-empting the quantitative interpretation, the primary emphasis in this study was to identify loosened tiles which would then presumably be tested using direct contact methods. A test panel was devised consisting of a loosened tile surrounded by four securely bonded tiles. The 15-cm by 15-cm tiles were mounted using standardized procedures onto an aluminum substrate in a cross like pattern as shown in figure 5. The center tile was then subjected to cyclic loading to loosen it to an extent that would warrant its replacement on the orbiter. Grid densities of 4 lines/mm were used for the testing. The analyzer grid was registered on photographic film and contact prints were made from it to serve as specimen rulings. Contact grids were deemed acceptable during this phase since they afford better fringe contrast and could be supplanted by projected grids if the tests proved otherwise suitable. The deployment of orthogonal grid orientations to cover all possible in-plane motions is shown at the bottom of figure 5. The analyzer grids were similarly oriented and placed approximately 1.5 cm from the tile surfaces. The horizontal grids were adjusted to be approximately parallel to form horizontal Moiré fringes most sensitive to vertical displacements. The vertical grids when parallel formed vertical fringes which were sensitive to horizontal displacements. Comparisons of differences in the motion of Moiré patterns of the loosened and more rigidly bonded tiles were more easily made with the vertical grids since the vertical fringe pattern movement was not affected by the rigid-body vertical displacement of the substrate.

The test panel was oriented vertically and subjected to vertical in-plane sinusoidal acceleration of 2 g (peak) by a 133 kN (30,000 lb) servo-controlled exciter. The frequency of the exciter was varied from 20 to 150 Hz which encompassed the natural frequencies of the tile-SIP system. The panel was illuminated with a large strobe lamp delivering on the order of 1 joule per flash and viewed with a TV camera. The rather elaborate camera system (with standard vidicons) described in reference 5 was used in lieu of less exotic models because of availability. A photograph of the setup is shown in figure 6.

With the shaker operating, several distinct features of the Moiré patterns were discernible with the strobe adjusted slightly below or above the exciter frequency. The following observations were made:

1. The slow excursions of the horizontal fringes past a fixed reference quantitatively (0.25 mm/fringe) tracked the shaker amplitude.

2. Motion of the vertical fringes attested to the nonlinear nature of the tile-SIP system (i.e., motion was induced transverse to the exciting direction).

3. The motion of the fringes on adjacent tiles was often out of phase and easily discernible. Zuckerwar and Sprinkle (ref. 3) noted such characteristics in their laboratory studies on tile debonding.

4. There was some indication of fringe "wagging" which implies rocking of the tile about a nodal line. The fringes remain stationary at the node while the "ends" sway back and forth as the surface moved to and fro. Although static views do not do justice to the phenomenon, two photographs of the video monitor are shown as inserts on figure 5. The photos attempt to capture the ends of excursion.

The results using contact grids suggest that relatively large areas could be surveyed using Moiré techniques to provide quantitative information on displacement and relative phase of neighboring tiles. The tile surfaces would require minor modification, perhaps during manufacture, by printing small orthogonal cross grids at one or two locations on the surface. Several small patches may not significantly alter the desired emissivity properties of the material.

If projected grids (sensitive only to out-of-plane motion) are used then no tile modifications are required. To determine the magnitude of out-of-plane motion small mirrors were attached to the tiles and used to reflect a low power laser beam as shown in the top of figure 7. The long moment arm magnified small angular displacements which were determined by measuring the excursions of the reflected beam. The results for the tile panel are shown in figure 7. It appears that if the sensitivity of the experiment were set to detect 0.10 degree then the Moiré pattern of the loosened tile would be seen to move while the patterns of adequately bonded tiles would not. This would occur over a rather broad range of excitation frequencies, thus providing a suitable "flag" for the suspect tile.

Figure 8 depicts a static picture of the projected fringes on a tile surface. The (4 line/mm) analyzer is displaced approximately 1.5 cm from the surface. The fringe contrast attests to the suitability of unmodified tiles for optical approaches. One-tenth degree out-of-plane rocking is easily detectable with this scheme. The analyzer grid could be removed several feet using optics to relay the master grid and its projection.

CONCLUSIONS

Moiré techniques appear to offer relatively simple means for detecting the small in-plane or out-of-plane displacements associated with loosened tiles when the tiles are periodically excited at 2 g (peak) in the laboratory. The use of projected Moiré fringes to detect out-of-plane rocking appears to be the best indicator of tile looseness since quantitative readout or modifications to the tiles are not required. If the Shuttle orbiter can be subjected to periodic excitation of 1 to 2 g (peak) and rigid-body periodic displacements do not mask the change in the Moiré pattern due to tile looseness, then the Moiré technique may prove useful as a simple, semi-global inspection tool for the orbiter tiles.

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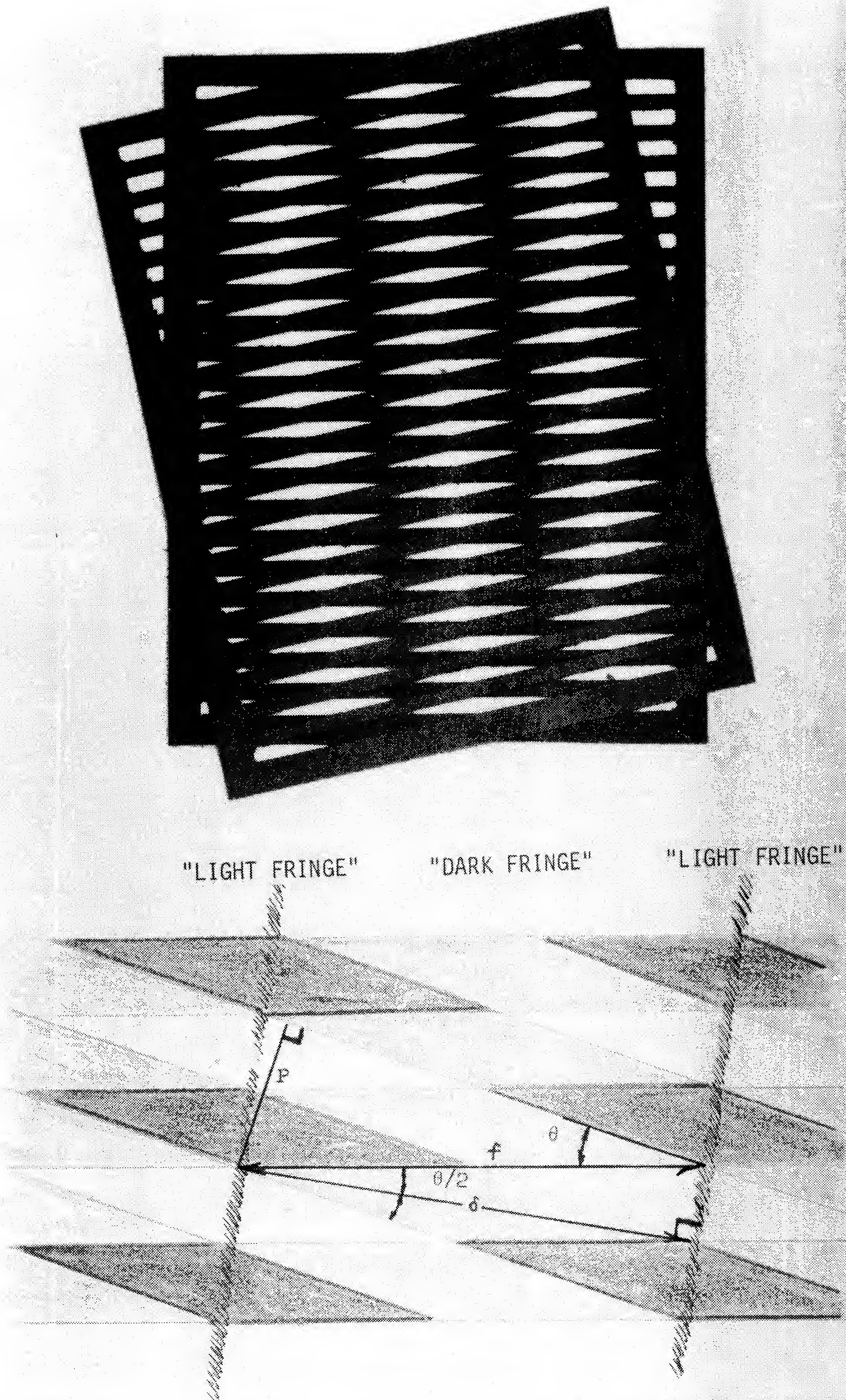


Figure 1. Geometry of moire fringes generated with linear grids.

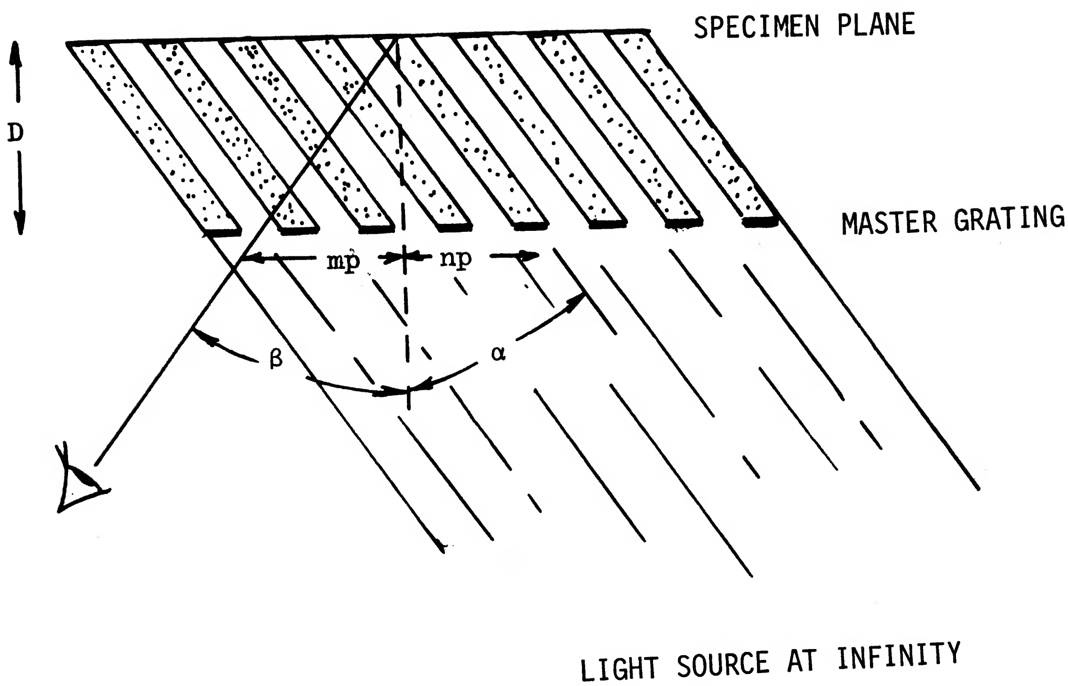


Figure 2. Geometric layout for projected grid scheme.

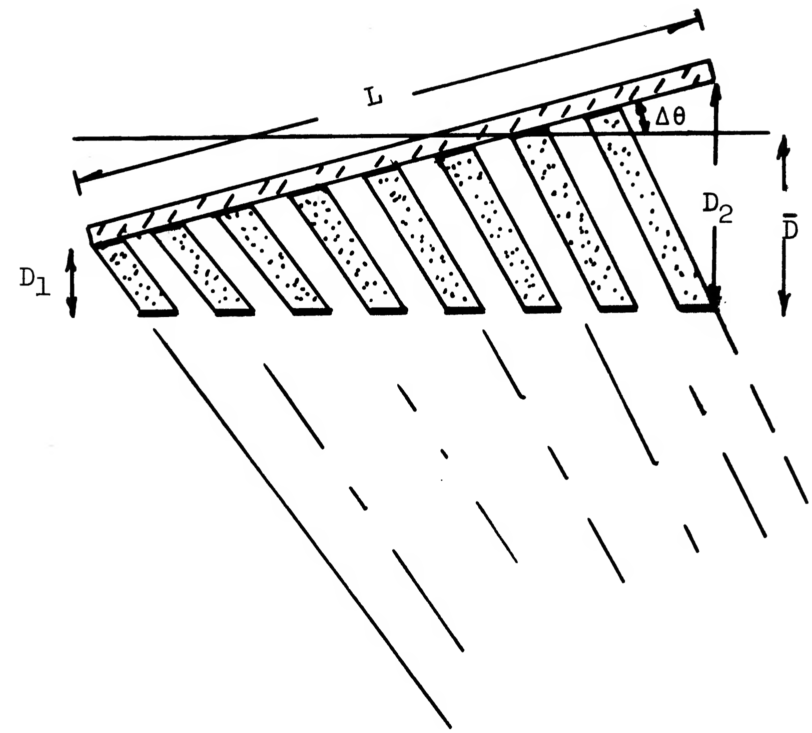
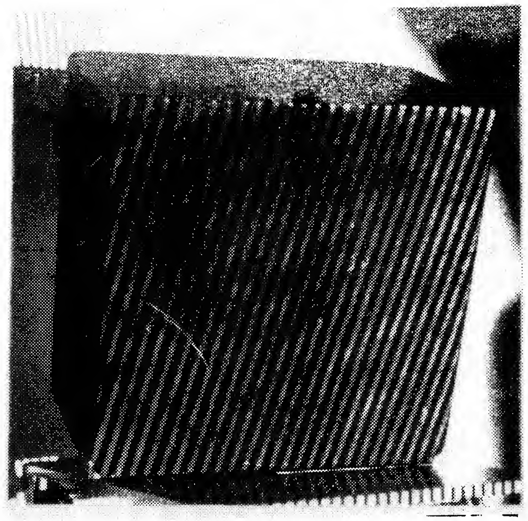


Figure 3. Sketch to illustrate out-of-plane rocking.



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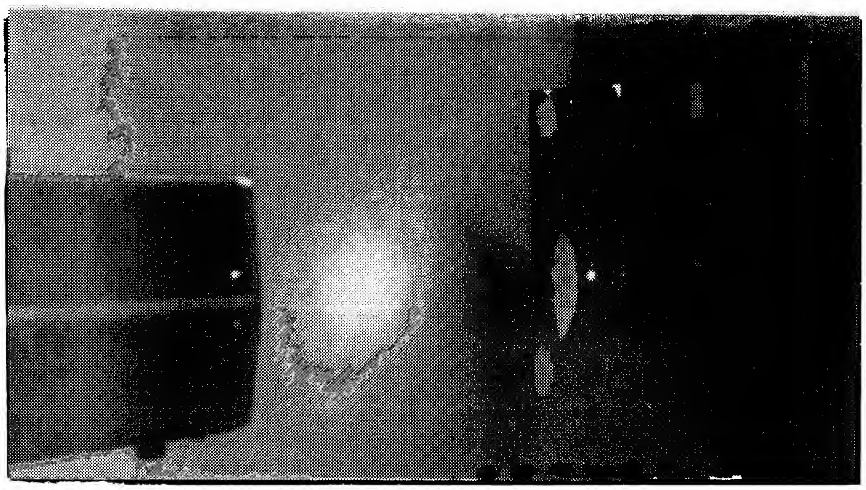

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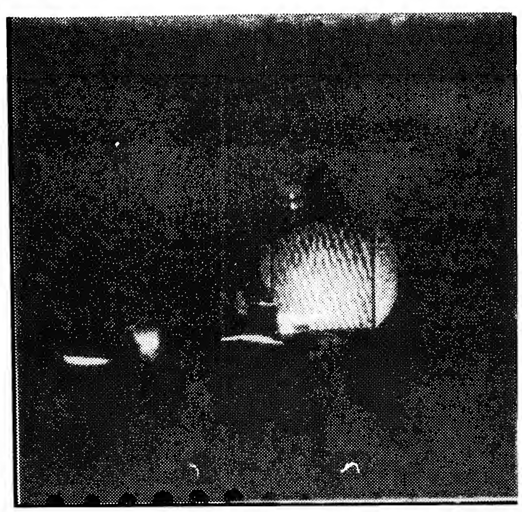
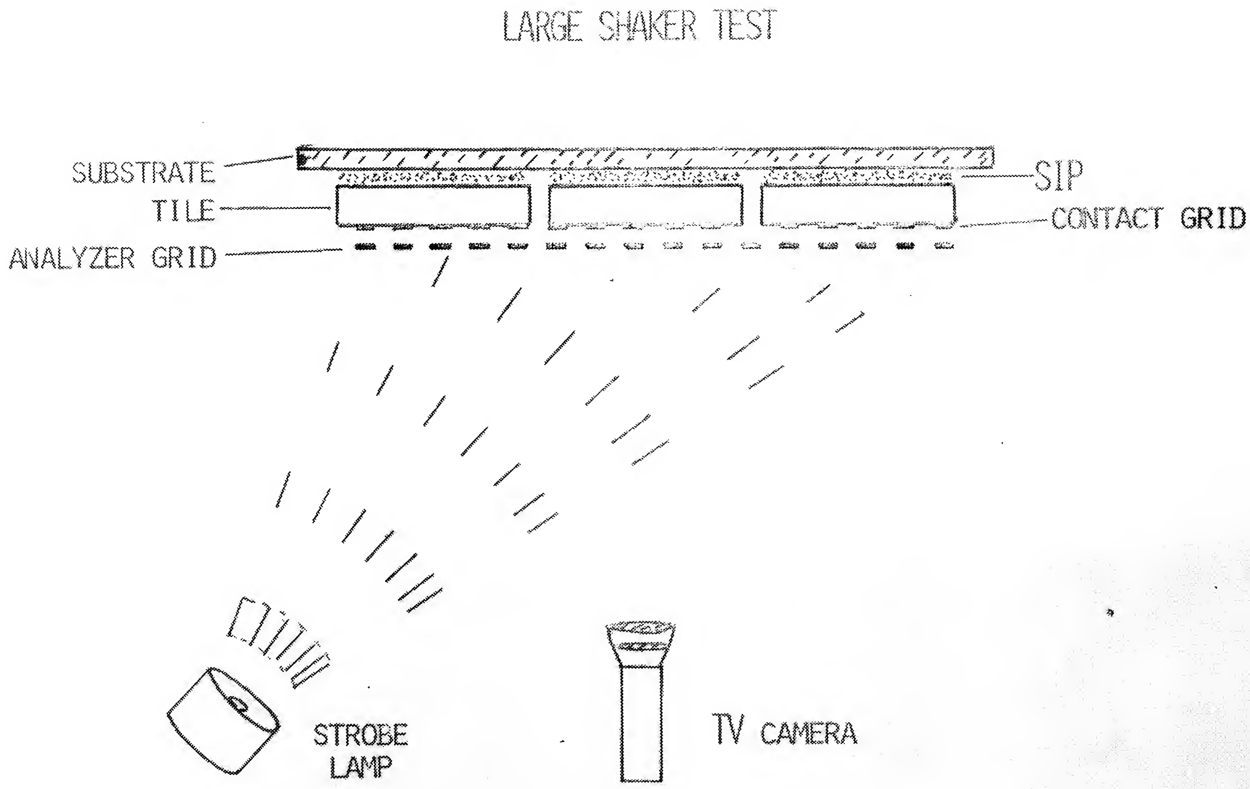


4c

Figure 4. Photographic properties of the tile. (a) Projected grids display remarkably good contrast. (b) Laser beam reflecting off tile surface. (c) 12 line/mm projected grid begins to detect surface structure.



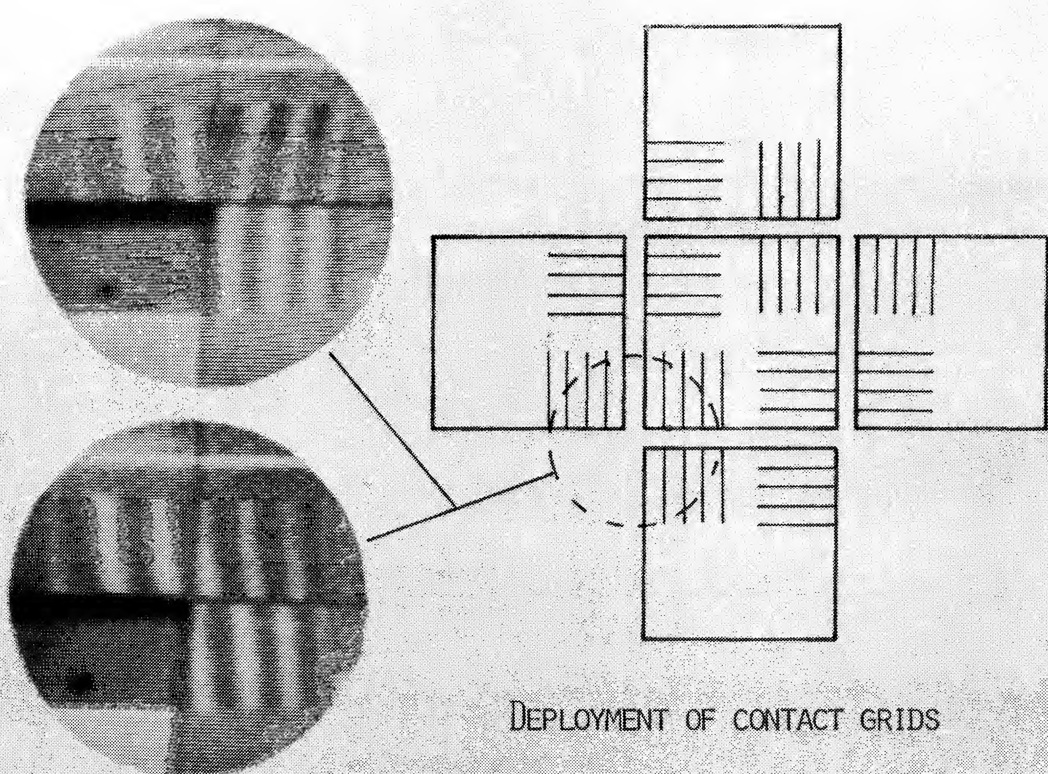


Figure 5. Schematic of test panel layout. Insert shows typical fringe data.

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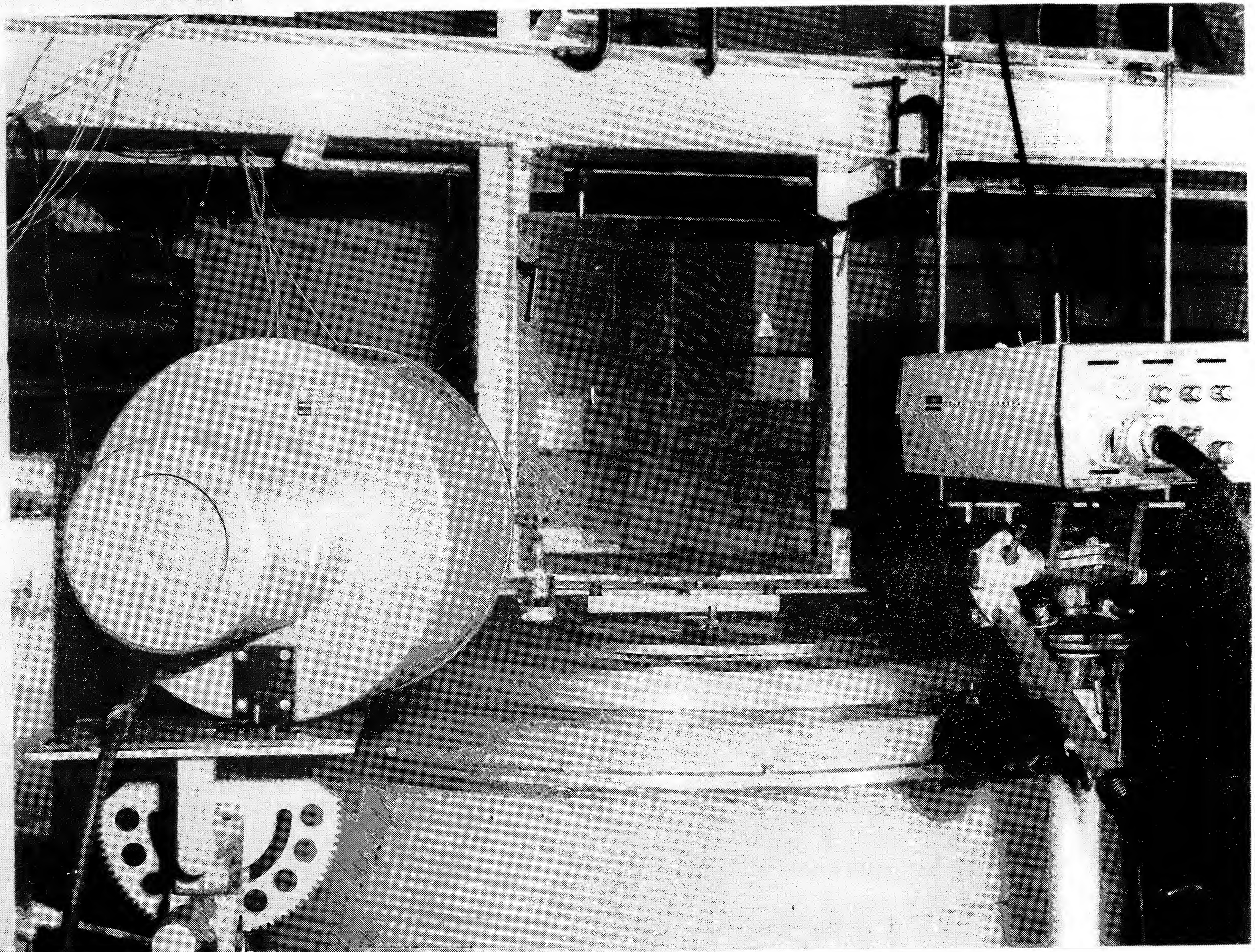
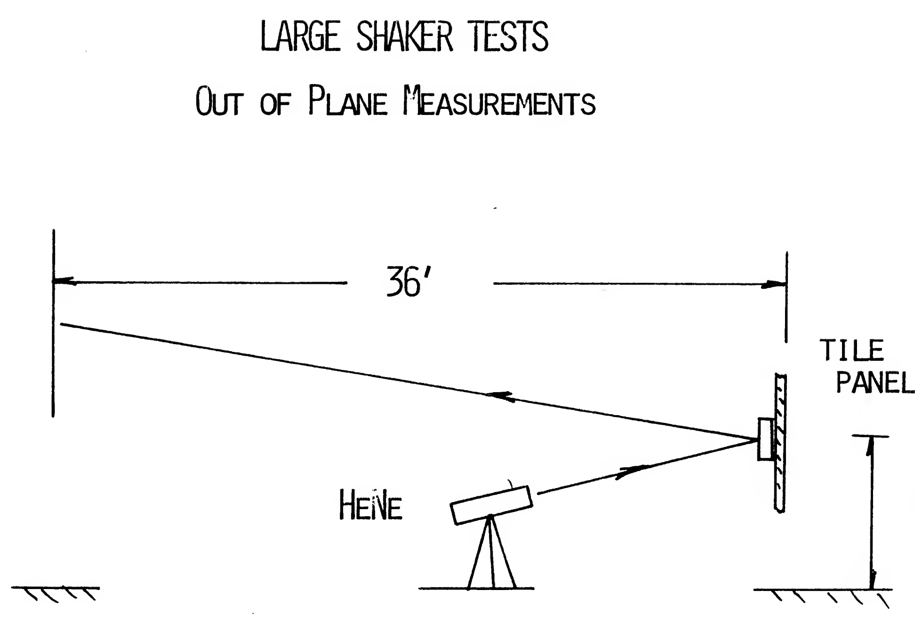


Figure 6. Photograph of experimental set up.



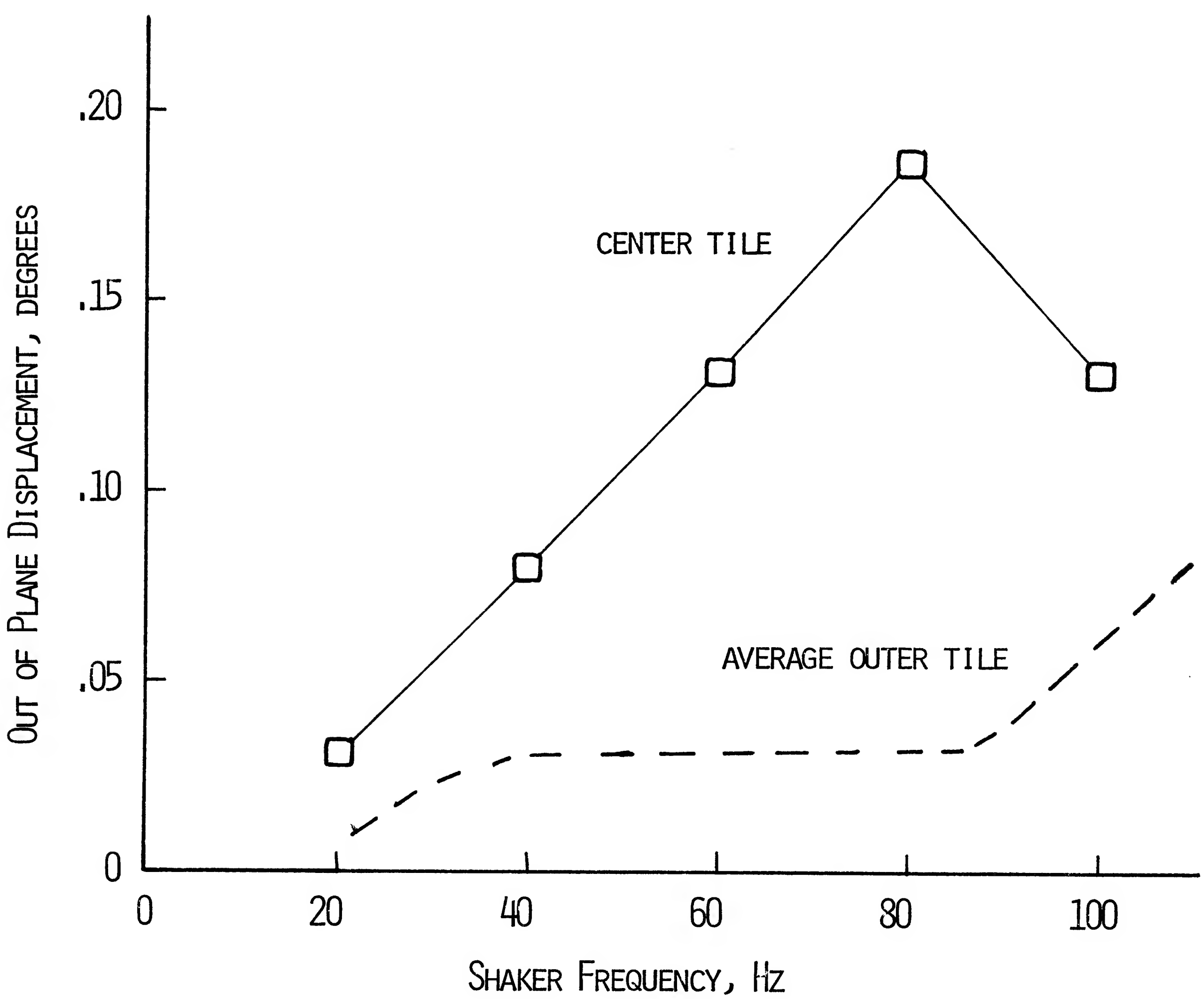


Figure 7. Experimental arrangement for measuring out-of-plane displacement and graph of results.

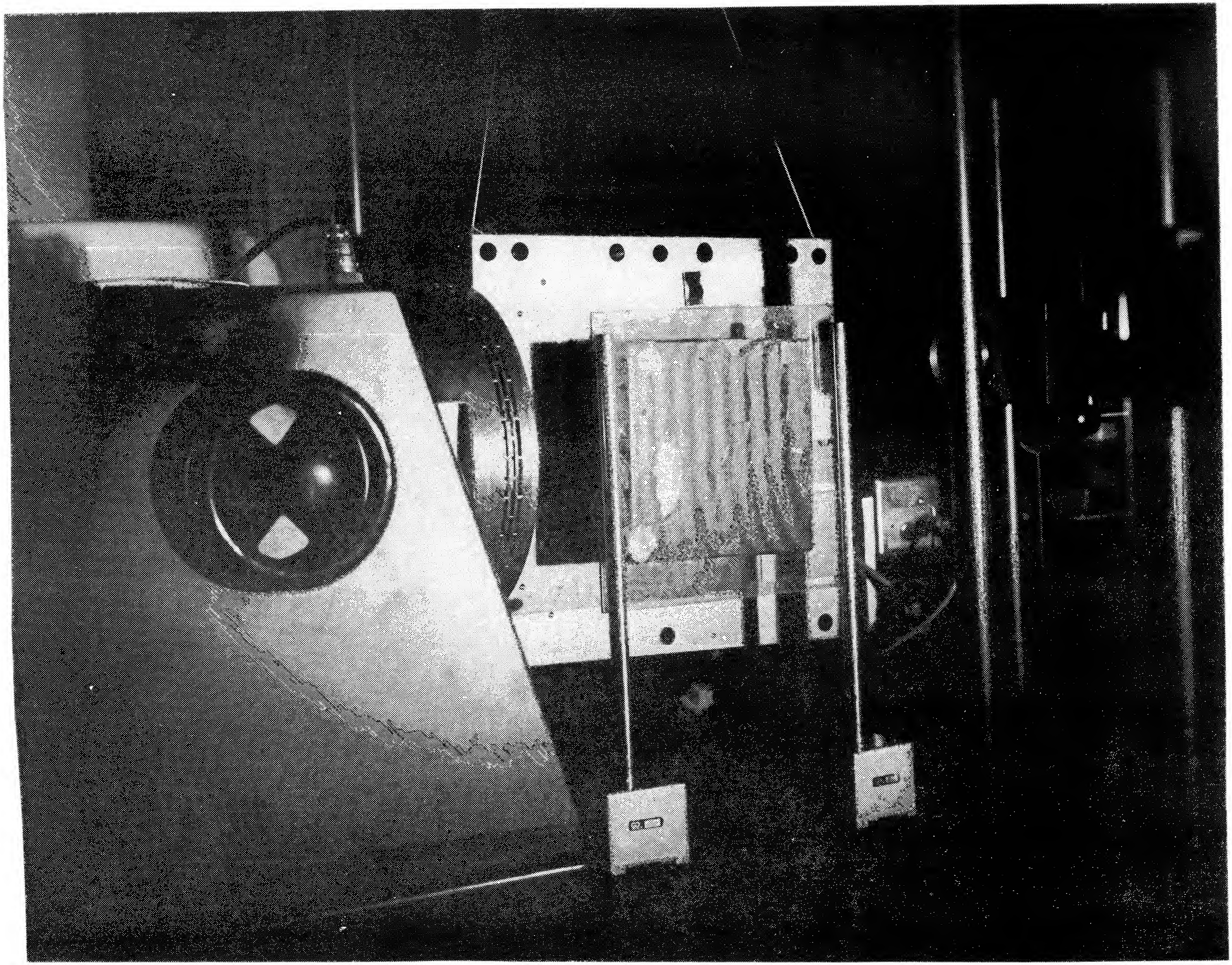


Figure 8. Laboratory mock-up of projected fringe scheme.

1. Report No.	2. Government Accession No.	3. Recipient's Catalog No.
NASA TM-83205		

4. Title and Subtitle	5. Report Date
Dynamic Moiré Methods for Detection of Loosened Space Shuttle Tiles	September 1981
	6. Performing Organization Code 506-89-01-01
7. Author(s) W. L. Snow, A. W. Burner, and W. K. Goad	8. Performing Organization Report No.
	10. Work Unit No.
9. Performing Organization Name and Address NASA Langley Research Center Hampton, VA 23665	11. Contract or Grant No.
	13. Type of Report and Period Covered Technical Memorandum
12. Sponsoring Agency Name and Address National Aeronautics and Space Administration Washington, DC 20546	14. Army Project No.

15. Supplementary Notes

16. Abstract

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17. Key Words (Suggested by Author(s))	18. Distribution Statement
Space Shuttle, Thermal Protection System, Recertification, Tile Response, Moiré	Unclassified - Unlimited Subject Category 35

19. Security Classif. (of this report)	20. Security Classif. (of this page)	21. No. of Pages	22. Price*
Unclassified	Unclassified	16	A02

*For sale by the National Technical Information Service, Springfield, Virginia 22161